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Abstract. A comprehensive study of charge breeding techniques for the most ambitious ISOL - facility project, EURISOL, is presented here. It is based on results obtained during the past years at CERN - ISOLDE and LPSC Grenoble with charge breeders of both ECR and EBIS types.

PACS. 29.25.Ni Ion sources: positive and negative – 29.38.-c Radioactive beams – 41.75.-i Charged-particle beams – 52.40.Mj Particle beam interactions in plasmas

1 Introduction

EURISOL is arguably the most ambitious proposed project for producing accelerated radioactive ion beams using the ISOL (Isotope Separation On Line) method [1]. The ISOL method produces radioactive ion beams in three consecutive steps: i) a primary beam impinges on a target where reaction products are stopped ii) the radioactive isotopes diffuse in the target material, and effuse towards a radiation-resistant source iii) after ionization and acceleration, the isotopes of interest are selected by a magnetic separator. Different sources for the ionization to 1+ are used, according to the element to be ionized. These are typically

- plasma sources (such as ECRIS or FEBIAD) for noble gases
- hot surface cavities (e.g. W, Ta or Rh) for alkali and alkali-earth elements
- plasma sources with hot surfaces (FEBIAD) or laser sources for other metallic elements with melting points around or below 2000 $^{\circ}C$.

Extracted as singly charged ions from the target-ion source units, the radioactive isotopes have to undergo a charge breeding process to an n+ state to match the limit in mass-to-charge-ratio of the post-accelerator. The study and development of charge breeding techniques plays a prominent role for optimizing the post-acceleration of intense and exotic beams that will be produced in EURISOL. High charge states, i.e. relatively low A/q-ratios, allow for compact ion accelerators and higher final beam energies, in particular in combination with superconducting LINAC structures [2]. This post-acceleration scheme, also known as 1+ n+ scenario, presents several technical challenges because of the diversity of the produced isotopes in terms of mass (spanning the complete nuclear chart), lifetime (short lived, 1ms to stable), produced intensities (from a few up to 10^{13} ions/s) and because of the combined rareness and short lifetimes of the most exotic isotopes. This article suggests a roadmap for the future charge breeding techniques to be developed for EURISOL. It is based on results from on-line experiments performed in the frame of the EURISOL Design Study at ISOLDE and GSI and more generally on experience gained at other charge breeding systems around the world.

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2 Charge breeding of ISOL beams

Because of the challenges listed above, the charge breeding technique used has to be universal, rapid and efficient. It needs to deliver sufficiently high charge states to allow the post-acceleration of ISOL-type ion beams produced by a EURISOL-like facility. It has to maintain the level of contamination from either isobaric or A/q, stable or radioactive contaminants within acceptable limits (usually a fraction of the beam of interest). Other parameters may additionally influence the choice of technique. The time between system failures, the time to repair and the maintenance requirements may also have to be considered in view of radioprotection issues, while different aspects of flexibility includes ease of charge state selection and continuous wave (CW) contra pulsed operation capabilities.

2.1 Charge breeding techniques

Up to now, mainly three charge-multiplication techniques are in use for the post-acceleration of radioactive beams. The first one is the stripping technique based on acceleration of low charged ions followed by subsequent stripping in a gas jet or thin foil. Although it is a very efficient method for the production of bare light ions, a lower efficiency is experienced for heavy ions for which the post-stripping charge - state distribution is wide, and multiple stripping stages have to be used. It also requires a pre-stripper section, with low frequency RF-structures for the extreme A/q-range, that accelerates the radioactive ions to the minimum energy needed for the stripping process. For example, at GSI the High Current Injector of UNILAC, a 30 m long, 36 MHz, 2 MW accelerator consisting of an IH-type RFQ and two IH-DTL cavities, is required to accelerate the ions to 1.4 MeV/u for the first stripping stage. The pre-stripper induces a significant additional cost to the facility [3]. This method, although the most rapid and robust one, might not be the best choice for EURISOL due to the drawbacks given above (although stripping can be used for additional purification of the beam from isobaric contamination). This option will not be further discussed.

The two other charge breeding techniques make use of either an Electron Beam Ion Source (EBIS) or an Electron Cyclotron Resonance Ion Source (ECRIS) as charge breeders. Literature describing these two devices can be found in [4–8]. During the last decade, a large amount of experience was acquired at ISOLDE with both breeder types.

First on the floor was the REX-ISOLDE preparation stage, consisting of a Penning trap (REXTRAP) for ion cooling and bunching combined with an EBIS (REXEBIS) for the breeding. REX-ISOLDE is routinely providing accelerated beams to users with energies up to 3 MeV/u, mainly for the purpose of nuclear structure experiments. A number of different radioactive beams have been accelerated, with masses ranging from ^{8}Li to ^{204}Rn, and with very different half-lives and chemical properties (alkali, metallic and noble gas ions), including fragments of molecular beams coming from ISOLDE.

Thereafter came a Phoenix ECR charge breeder, purchased by the CCLRC Daresbury laboratory. It was tested on a beam line of the General Purpose Separator (GPS) often using beams in a parasitic mode. The primary aim was to compare the performances of this ECR booster with the preparation stage of REX-ISOLDE [9]. A secondary objective was to make use of the charge breeding technique for nuclear physics experiments. Beam purification for the study of neutron-rich nuclides was successfully demonstrated during two experiments [10,11]. During the past years, the efficiencies of the Phoenix booster were characterized with a variety of stable and a few radioactive beams. Both the natural CW mode of operation of the booster, and the afterglow mode were tested. Based on the unique experience gathered with both charge breeders, this document reports on the possibilities these techniques could offer to the future EURISOL facility. Some input from test benches and solutions used at other facilities, such as GSI, GANIL, TRIUMF and TRIAC are also taken into account.

2.2 Key parameters for an EBIS

The EBIS was extensively discussed in review papers such as [4,6]. The main parameters that will determine the performances of an EBIS are:

- *The electron beam characteristics*, i.e. total electron current I_e, electron current density j_e and electron beam energy E. The effects of I_e and j_e are discussed below. The electron beam energy mainly determines the maximum reachable charge state, but it also affects the cross section for electron-impact ionisation.
- *The magnetic field*, which compresses the electron-beam to the required current density. Stronger magnetic field leads to a shorter breeding time, but also a smaller transverse trapping acceptance.
- *The design of the trapping region*, especially the trap length L. Primarily the charge capacity and pulse length are affected by the trap length.

The charge capacity of the trap can be readily calculated as:

$$Q = 3.32 \cdot 10^{11} \times f \times L \times I_e \times E^{-1/2} \tag{1}$$

where Q is the maximum number of positive charges that can be trapped, f is the actual electron beam compensation factor (attainable values between 0.5 and 0.7), L is given in m, I_e in A and E in keV. As the EBIS is essentially a pulsed charge breeder, one usually defines the charge breeding time τ as the time between injection of the 1+ ions and the ejection of the charge bred ions. During the trapping time the ions undergo step-wise ionization. The charge state distribution depends on the product $j_e \times \tau$, i.e. higher charge states are either obtained by increasing the current density or the breeding time as illustrated in Fig. 1 for Ar with $E = 5$ keV, which is a result from a CBSIM [12] simulation where charge exchange and radiative recombination processes were neglected. For a non-compensated electron beam, the acceptance of the EBIS will mainly be defined by the electron beam diameter, the magnetic field strength and in case of the accumulation mode the electron beam intensity [13,14].

A detailed description of REXEBIS can be found in [15]. The main characteristics are given in table 1. As the REXEBIS is essentially a pulsed device, and as its transverse acceptance is rather small compared to the ISOLDE beam emittances, a bunching and cooling device is required. REXTRAP, a Penning trap filled with a buffer gas, usually neon, performs these operations [16]. As one bunch is accumulated when the other is charge bred, the total preparation time is at least twice the charge breeding time. A brief summary of the performances of REXTRAP is shown in table 2. After REXEBIS a two-stage separator [17] allows a selection in energy and A/q of the beam with an achieved resolving power of $(A/q)/\Delta(A/q)$ ~150 prior to its post-acceleration in a LINAC. Fig. 2 and 3 present a

Table 1. REXEBIS main characteristics.

B-Field	2 T
Electron beam	Cathode LaB_6 $j_{cathode}$ <20 A/cm^2 $j_{trap}/j_{cathode} \sim 10$; $j_e = j_{trap}$ <200 A/cm^2 I_e=460 mA (normal operation 200 mA) E=3.5-6 keV
Trap	3 drift tubes L=200 to 800 mm Theoretical capacity 5×10^{10} positive charges
Acceptance	11 mm·mrad (95% geometrical) for 60 keV– estimated for $A \simeq 30$ [15]
Emittance out	15-20 mm·mrad (95% geometrical) for 20·q keV – measured with a non separated beam [13]
Max. energy spread	50 q·eV - estimated [15]
Pulse length	FWHM 40 to 300 μs
Vacuum	10^{-10}-10^{-11} mbar

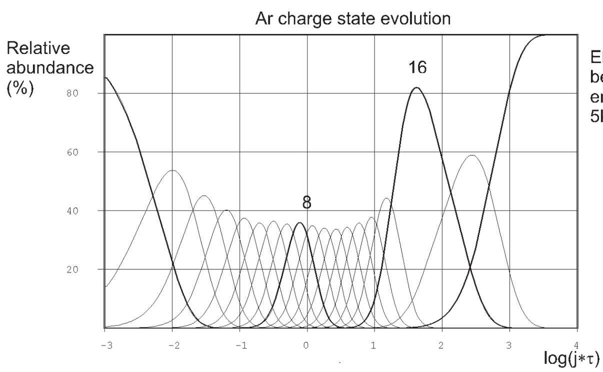

Fig. 1. Ar charge state distribution as a function of $j_e \times \tau$ for E=5 keV, as calculated by CBSIM.j_e is in A/cm^2 and τ in s.

Table 2. Summary of REXTRAP performances.

Efficiency	~50% for A >10 15-25% for A <10
Minimum cooling time	10 ms
Emittance out	10 mm·mrad at 30 keV (80%)
Pulse length	<10 μs
Space charge limit	10^8 ions/bunch

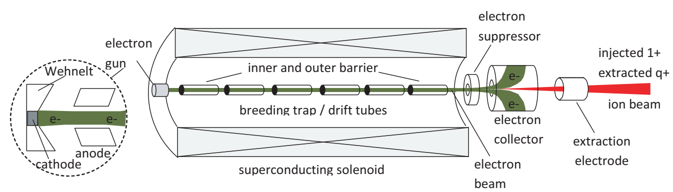

Fig. 2. Simplified cross-section view of an EBIS.

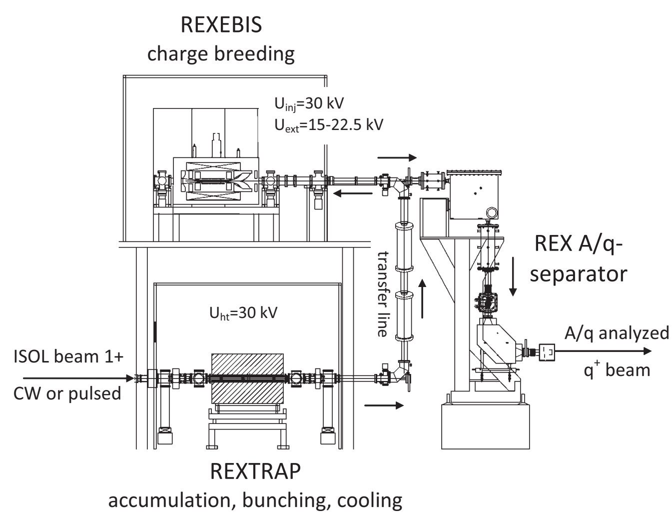

Fig. 3. Low energy stage of REX-ISOLDE: REXTRAP, REXEBIS and the A/q- and E- separator.

schematic cross-section view of a typical EBIS and the low energy stage of REX-ISOLDE. Eventually, an upgrade [9] of this kind of charge breeder could result in characteristics similar to the RHIC-EBIS [18], presented in table 3. An intermediate step is the MSU EBIT charge state breeder, which is mentioned briefly in section 2.7. In these cases, the preparatory cooling would not necessarily be needed, as the transverse beam acceptances are much larger than for the REXEBIS. This high performance breeder could therefore be operated with a continuous ion injection (see section 2.4) and the Penning trap would become redundant.

2.3 Key parameters for the ECR charge breeder

The main parameters of an ECR charge breeder are given below. A more complete description of this type of charge breeder can be found in [7,8,20,21].

– *The frequency of the RF wave (f_{RF}).* A higher frequency shifts the charge state spectrum to higher charges and permits shorter charge breeding times. When increasing the operational frequency the confining magnetic field of the source has to increase correspondingly in order to maintain a closed resonance surface

Table 3. Some of the RHICEBIS characteristics, from [18].

B-field	6 T
Electron beam	Cathode IrCe $j_{trap} > 575$ A/cm^2 I_e=10 A E=20 keV
Trap	L=1.5 m Theoretical capacity $1.1 \cdot 10^{12}$ positive charges Measured capacity $3.4 \cdot 10^{11}$ positive charges (with TestEBIS I_e=8 A L=0.7 m)
Acceptance	20 mm·mrad (RMS) at 11 keV- estimate from [19] $\sim$ 80 mm·mrad (90%) at 11 keV
Beam emittance out	0.36 mm·mrad 90% normalized, measured with 17 keV/u, Au^{32+} $\sim$15 mm·mrad 90% physical emittance Lighter beams (like He^{2+}) have normalized emittances up to 1.2 mm·mrad
Energy spread	1.5 q·keV
Pulse length	10-40 μs (using fast extraction)
Vacuum	10^{-9} - 10^{-10} mbar

at a certain distance from the plasma container walls. The scaling laws [7,8] suggest that the electron density n_e is on average close to the cut-off density and therefore proportional to the square of f_{RF}, at least in the range from 2.45 to 28 GHz. Theoretically, as in the EBIS case, the stepwise ionization process leads to charge states increasing with the product $n_e \cdot \tau$, where τ is the time for reaching charge equilibrium. In practice, this time is much shorter than the charge confinement time. This latter accounts for most of the charge breeding time τ_{cb}, defined in the following as the time between the injection of the 1+ beam and the time when the associated n+ beam current reaches 90% of its maximum value, adopting the same definition as in [22].

– *The topology of the magnetic field confinement and the magnetic field amplitude.* A minimum-B structure is usually established to provide magnetohydrodynamics (MHD) stabilization and to create a topologically closed region at which the condition for a resonant excitation of the electron cyclotron motion is fulfilled, i.e. $f_{RF} = eB/m_e$. For this kind of confinement, a magnetic field minimum is created in the middle of the plasma chamber by combining 2 or 3 solenoids aligned along the axial direction with a magnetic multipole structure in the radial direction. Depending on the application, simpler structures can be used. In the case of the afterglow mode, which is a pulsed operation of the charge breeder, a strong confinement is required. The trapping time will depend directly on the magnetic mirror ratios at the injection and extraction sides of the booster.
– *The type and flux of the support gas.* The power required to sustain or ignite the plasma as well as the charge exchange processes will depend on the nature of the support gas. Typically oxygen or helium are used. As it usually constitutes the major component of the stable background, heavy gases are to be avoided to limit the number of peaks contaminating the A/q spectrum. In addition, the charge state distribution is affected by the support gas type [23].
– *The walls of the plasma chamber.* As mentioned before, the confinement should be sufficient to prevent plasma leaks to the wall that will induce heating and degassing. The material of the plasma chamber can be chosen in order to modify the electron density. For example, the use of aluminium has shown a beneficial influence on the production of high charge states due to the high secondary electron emission capabilities. In the case of radioactive ions one should be aware of the sticking time of the ions to be charge bred, and of the impurities contained in the plasma chamber material, to avoid unwanted background.

Two modes of operation can be used with the ECR charge breeder [20]. The natural mode is continuous injection and extraction. In this mode of operation, the charge breeding time τ_{cb} as defined above includes the charge breeding process to reach charge equilibrium and the hold-up time of a given charge state. In practice it about equals the charge confinement time. A pulsed operation mode is the so-called afterglow or ECR Ion Trap (ECRIT) mode [20,21,24,25]. In this mode, the rate of ion extraction is suddenly increased during the plasma decay induced by a rapid RF power switch-off. When the RF wave is suddenly stopped, the electrons of the plasma escape, as energy is transferred from the magnetic moment by collisions, and the plasma confinement collapses. This ejects the multi-charged ions towards the lowest magnetic field region, i.e. the exit coil. Here, the charge breeding time τ_{cb} is defined as the average time between 1+ injection and the switch off of the RF. Between the extraction pulses the magnetic field configuration has to allow accumulation, trapping and charge breeding of the ions injected into the plasma. Because of this cycle of continuous accumulation, charge breeding and pulsed extraction, the afterglow mode of an ECR is similar to the continuous injection mode of an EBIS (section 2.4).

Some of the characteristics of the Phoenix ECR breeder used for the charge breeding tests are listed in table 4. The

Table 4. Some characteristics of the Phoenix charge state booster. B_{inj}, B_{ext}, B_{min} and B_{ecr} refer respectively to the typical magnetic fields at the injection and extraction sides, to the minimum field between them, and given the 14.5 GHz frequency to the field corresponding to the resonant excitation of the electron cyclotron motion.

RF frequency	14.5 GHz Max power 1 kW
Magnetic confinement	B-minimum structure 3 axial coils and a permanent magnet hexapole structure B_{inj}=1.5 T, B_{ecr}=0.52 T ; B_{min}=0.5 T; B_{ext}=1 T; B_{rad}=1.35T Mirror ratios B_{inj}/B_{min}=3; B_{ext}/B_{min}=2
Plasma chamber	$\sim$ 1 l volume Stainless steel
Acceptance	$\gtrsim$55 mm·mrad at 20 keV (90%) [22]
Emittance out	<80 mm·mrad at 20 q·keV (90%)
Energy spread	1-10 q·eV
Vacuum	$< 10^{-6}$ mbar in the injection and extraction regions 10^{-7} mbar without plasma
Support gas injection	O_2 at $5{\cdot}10^{-5}$ mbar·l/s

test bench is presented in Fig. 4 and a cross-section view of the Phoenix booster in Fig. 5.

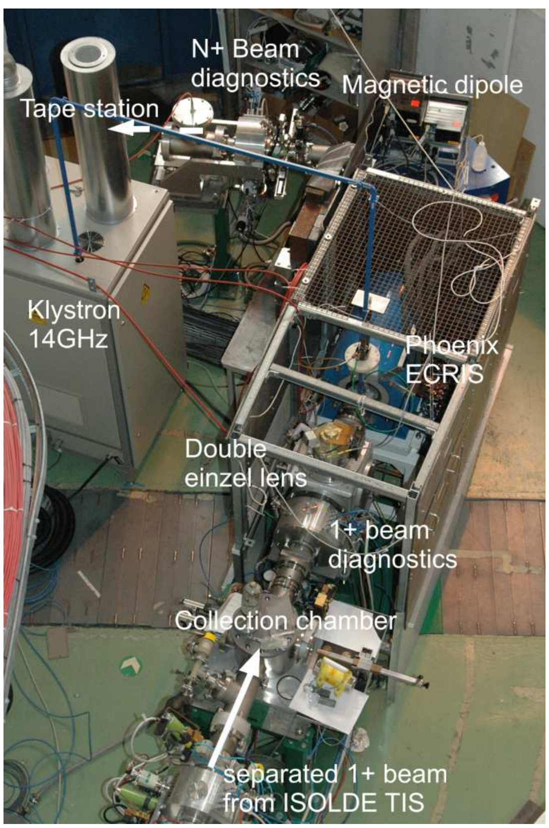

Fig. 4. The ECR Phoenix booster test bench at ISOLDE.

As any high performance ECR ion source producing multiply - charged ions, the Phoenix charge breeder has a plasma density close to the cut-off and can therefore handle very intense beams. Its plasma characteristics are not perturbed by the injection of beams up to the μA regime, for which charge breeding efficiencies can be maintained to the same level [21]. In pulsed mode up to 400 nA of Rb^{1+} was injected in MINIMAFIOS [20,25], a rather modest charge breeder compared to the Phoenix booster. Pulses of a few 10^{10} Rb^{15+} extracted over a length of 20 ms could be produced, corresponding to more than 10^{11} Rb ions integrated over the whole charge state spectrum. Because of its sufficient transverse acceptance, ion coolers are not necessary prior to the injection of the 1+ beam. However, a large energy spread of the injected ions can spoil the injection efficiency due to the narrow energy acceptance of the ECRIS plasma. Of related importance is the potential difference ΔV between the acceleration voltage of the primary beam and the high voltage of the booster. The optimum potential difference is dependent on the 1+ ion source type and on the nature of the injected beam [21]. For alkali and metallic ions, the ΔV acceptance will be of the order of a few volts only, which can eventually limit the efficiency if 1+ sources with a large energy spread are used. On the other hand, an accordingly small energy spread is expected for the n+ beam released from similar fields than the ones used to capture the 1+ beam.

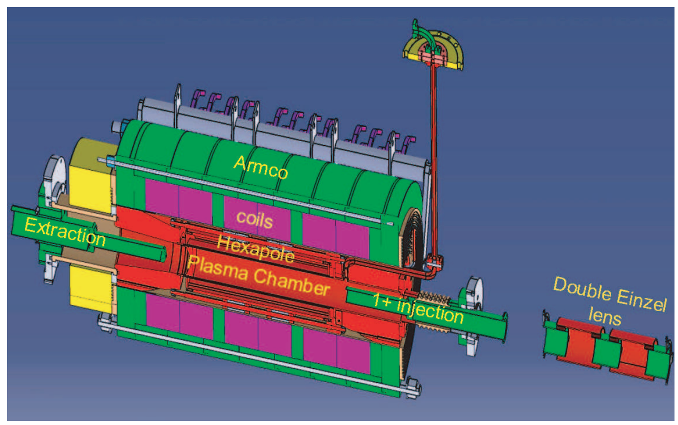

Fig. 5. 3D cross-section view of the Phoenix ECR charge breeder.

Potentially, almost any kind of ECR ion source can be transformed into a charge breeder system, the main change being the insertion of a grounded axial tube permitting the injection of the 1+ beam. This change may entail a modification of the RF power injection system, in case its original configuration is axial. The most advanced ECR ion sources in the world are SECRAL [26], VENUS [27], MS-ECRIS [28], SuSI [29] and A-PHOENIX [30]. While the first ones are fully superconducting systems, the last is a hybrid system combining High Temperature Superconducting (HTS) coils and a permanent magnet hexapole. The frequency injected in these ion sources is 28 GHz with typical axial and radial B-values of 3-4T and 2T respectively. The SECRAL, VENUS and SuSI sources are in operation while A-PHOENIX is being commissioned and MS-ECRIS is still under construction. The development of charge breeding capabilities for some of these devices is foreseen. Lately, the prototype of Phoenix charge breeder developed by LPSC, Grenoble was further optimized to enable double RF frequency operation (14 and 18 GHz), and to obtain a more symmetric magnetic field configuration at the injection side where the RF is injected. Additionally the support gas is now directly injected into the plasma chamber.

2.4 REXTRAP/REXEBIS performances

Fig. 6 and 7 present an overview of results from 2008 showing trends for the charge breeding times and low energy preparation efficiencies (REXTRAP + REXEBIS). Previous results were published in [31] and [32]. REXTRAP is routinely performing with an efficiency of around 50-60%. The efficiencies of the REXEBIS alone are therefore about twice as high as presented in Fig. 7. Particularly good efficiencies for K^{9+} and Cu^{19+} can be explained by closed shell effects. A/q-values below 4.5 and most generally around 3-4 are used for post-acceleration by the REX-ISOLDE LINAC. The breeding times were therefore tuned accordingly. As part of the overall beam preparation, the cooling time in the REXTRAP has to be added to the charge breeding time for a fair comparison with the ECR charge breeding times shown in the next section. For synchronization purpose, the cooling and bunching time has to be equal to the charge breeding time, thus the total preparation time amounts to twice the one shown in Fig. 6.

Usually, a 50 Hz repetition rate is used for masses below 40, as a minimum cooling time of 20 ms has to be applied to obtain good injection efficiency into REXEBIS. The results presented in Fig. 6 and 7 were obtained either during stable beam setup of REX-ISOLDE, or during the actual runs with the radioactive beams. The intensities of the injected beams were always below the space charge limitation of the trap ($\ll 10^8$ ions per bunch, see table 2) in the range from 1 to 100 pA. In addition to these beams, the use of molecules has been shown to be a very powerful way of producing isobarically pure beams. An example is the first successful experiment performed with ^{70}Se [33]: $SeCO^+$ molecules were cooled in the trap, then broken up and charge bred in EBIS to Se^{19+}. Two successive mass-over-charge separations permitted an excellent suppression of the contaminants. The first selected the molecule $SeCO^+$ (mass 98) after the ISOLDE HRS, while the second one selected the molecule fragment with mass-over-charge ratio (A/q=70/19) after the EBIS. Since then, several molecular beams have been injected and their fragments post-accelerated at REX-ISOLDE, such as ^{10}C from CO, ^{96}Sr from SrF and $^{140-142}$Ba from BaF. A detailed report on the use of molecular beams at REX-ISOLDE and with the Phoenix ECR can be found in [34] as part of the EURONS activities.

Until now, the use of REXTRAP for ion cooling and bunching has been found necessary in most of the cases to match the limited acceptance of REXEBIS in transverse and longitudinal direction for an optimum charge breeding efficiency. The pulsed injection requires a fast pulsing of the collector barrier potential and a bunch length shorter than the time of the round-trip in the electron-beam trap. Another mode, the so-called "accu-mode" [35] allowing continuous injection has also been used during a beam

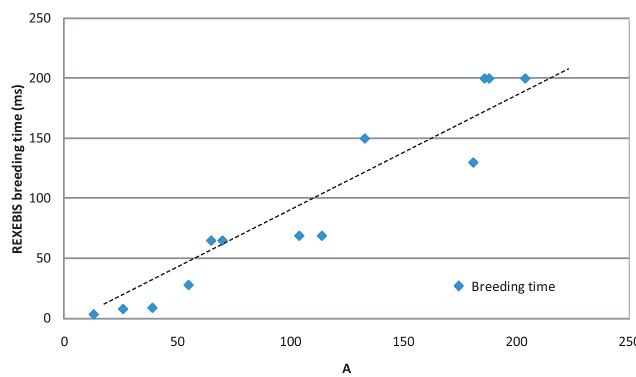

Fig. 6. REXEBIS charge breeding time for reaching A/q <4.5, as required by the LINAC, for isotopes charge bred in 2008. The cooling and bunching time from REXTRAP - equal to the charge breeding time - has to be added to account for the complete hold-up time in the low-energy ion preparation stage.

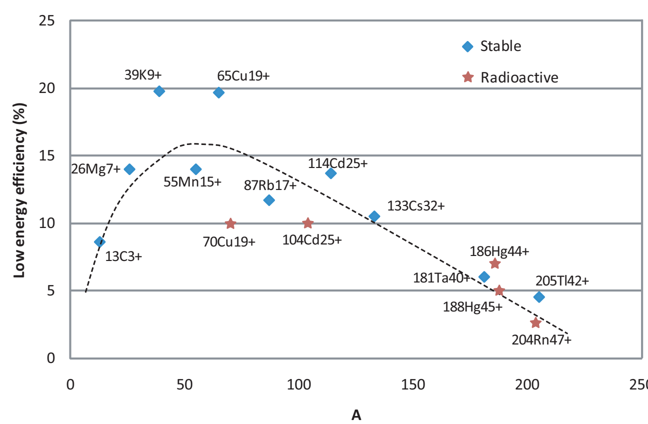

Fig. 7. Low-energy preparation stage efficiencies for isotopes charge bred in 2008.

time because of a temporary failure of REXTRAP. The accu-mode necessitates injection of the ions slightly above the collector barrier and successive ionisation to a higher charge state within the round-trip time. Ions remaining singly charged are not confined in this injection scenario, meaning that the efficiency might be lower. While the injection takes place the electron beam becomes partially neutralized with newly captured ions. A partially neutralised electron beam can be considered as a well-defined target of ions. Such a Coulomb target provides friction to the movement of newly injected ions and can enhance the trapping of the low-charged injected ions. Extensive injection simulations have been performed for the MSU charge state breeder [14,39]. The results show that a reasonable overlap of the ions with the electron beam is required to reach the required charge state. The transverse acceptance of the EBIS also improves with larger electron beam diameter. At REXEBIS, accu-mode tests were carried out using a CW beam from a reference ion source and from ISOLDE with emittances in the order of 10-20 mm·mrad (90%) at 30 keV, optionally cooled by the RFQ cooler ISCOOL to emittances of about 3 mm·mrad [36,37]. The beams were shot through a non-active REXTRAP with 75% efficiency and injected over a lowered outer barrier in the EBIS. An efficiency of 4% for $^{39}K^{9+}$ was reached for 9.5 ms breeding time for injected beam currents up to 500 pA. A slightly higher efficiency of 5% for $^{87}Rb^{17+}$, breeding time 29 ms, was achieved with a cold injected beam from ISCOOL. The results of these tests are more extensively discussed in [34]. This mode of operation is particularly interesting for high intensity beams, as expected from an HIE-ISOLDE upgrade [9], for which REXTRAP would become a limiting factor ($\gtrsim 10^8$ ions/bunch, see table 2).

In addition, a slow extraction mode was successfully developed and used during physics runs to limit the instantaneous beam throughput of the accelerator to the MINIBALL experiment and the detectors [38]. The EBIS pulse was extended from 40 to 400 μs without any efficiency loss, and could possibly be further enlarged if it was not limited by the RF pulse of the LINAC (800 μs effective time) [40].

2.5 14GHz Phoenix Booster performance

Results obtained with the Phoenix ECRIS setup at ISOLDE were discussed in [11] and at conferences in [41,42]. Fig. 8 presents ΔV tuning curves from [11], while Fig. 9 is a compilation of results from [10,11,41,42] including LPSC data [21] and previously unpublished results.

The ΔV curves shown in Fig. 8 were measured during different experimental shifts periods at ISOLDE for different isotopes. I/I$_{max}$ is the normalized intensity of the extracted charge state of interest and ΔV is the potential difference between the ECR charge breeder and the 1+ source. The ΔV acceptance window derives from the fact that 1+ ions which are injected with too high energy pass through the ECR plasma without being stopped, while 1+ ions with an energy significantly lower than the plasma sheath potential are being reflected. In the stopping process the long range ion-ion Coulomb collisions are believed to play a predominant role and to be particularly efficient when the velocity distributions of the plasma ions and injected ions are similar [43].

The shape of the curve is influenced almost entirely by the chemistry of the elements (whether the injected element is stable or condensable), while the peak position is dependent on the type of 1+ ion source. In the case of noble gases, the ions injected with energy higher than the ECR plasma will have a non-negligible chance of getting recycled from the plasma chamber walls which is not possible for condensable species. This explains the plateau observed at negative ΔV for noble gases and its absence for condensable elements, for which direct capture is the only possibility. The difference in position for the different ion sources can be explained by the relative kinetic energy difference of the 1+ beam produced in the respective ion sources. In the case of the surface ionization source, the 1+ ions energy is well defined by the high voltage of the 1+ source. The ΔV curve has a maximum for a potential of the charge breeder close to the potential of the 1+ source minus the sheath potential of the ECR plasma. In the case of the FEBIAD (plasma source), the plasma of the 1+ source exhibits a negative potential that increases the absolute value of the ΔV curve maximum. The knowledge of the 1+ beam energy for a given ion source makes the ΔV tuning much simpler but is not mandatory as its optimum value is quite reproducible, as can be seen in Fig. 8.

A graphic representation of the Phoenix booster performance is shown in Fig. 9. Mass numbers have been indicated for the radioactive isotopes. The trend lines on the graphs are only meant as guides for the eye. Charge breeding efficiencies for one charge state vary between 12% for Ar to 2% for heavy elements (Z>80). The efficiencies for noble gases are higher than those for condensable elements

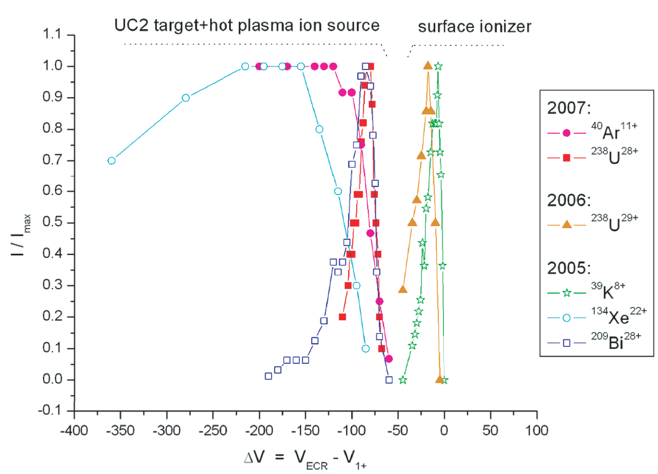

Fig. 8. Normalized beam intensities as function of the potential difference between the 1+ source and the Phoenix ECR charge breeder.

as the former can be recycled from the plasma chamber walls even at room temperature. Condensable species may only be captured directly into the ECRIS plasma. The injection process of light (Z<10), condensable elements has shown to be quite inefficient. In this case it is believed that the velocity mismatch between the light ions and the ions of the plasma hinders the capture because of the weakness of the ion–ion collision stopping force [43]. In the review paper [21] the author quotes 1.5% efficiency for Na^{6+}, and gives some preliminary ideas on how to improve the trapping of these fast ions, such as a tuneable position of the injection tube. Phoenix exhibits typical A/q-values ranging from 4 for the lightest ions to 8 for heavy ions (Z>80). The charge breeding times measured at ISOLDE indicate that on average about 10 ms is needed per charge. However, recent results at LPSC have shown that about 3 to 4 ms per charge could be reached at the price of somewhat lower efficiency [34].

As for the EBIS breeder, the injection of molecules was successfully proven. LaO^{+} molecules could be injected, broken-up, and the La^{+} fragment charge bred to charge state 23+ [42]. A first attempt with light molecules CO^{+} did not give any conclusive results.

Two series of tests were conducted using a pulsed mode of the ECR charge breeder. The first one was performed injecting Kr and Xe beams. Extracted afterglow pulses were produced at a frequency of 10 Hz and with 10 ms duration time. The results are presented in table 5. These are believed to not be fully optimized. Rather low efficiencies and modest charge states were obtained in spite of long charge breeding times. Some better results with Rb ions were shown for the MINIMAFIOS by Chauvin et al. [25] and are presented as for comparison in the same table.

A second test was done while trapping the recoil ions $^{61}Fe^{12+}$ coming from the decay of charge bred ^{61}Mn isotopes. This test is extensively described in [11]. A detailed off-line analysis of the recorded data indicated possible traces of recycled ^{61}Fe.

As for any ECR ion source, the use of support gas, the relatively high residual pressure and sputtering from the plasma chamber walls result in a high stable background. Charge recombination in the extraction region causes long tails in the A/q peaks. After the magnetic separator used in these tests, a few nA of stable beam was visible in the region 3<A/q<7, even away from the most abundant charge states of C, N, and O. The installation of an additional separation stage for energy selection, similar to the one in the REX separator, should significantly decrease the background level [44].

As a last remark, an upgraded version of the Phoenix booster including UHV components, double frequency injection system and an optimized magnetic field has been developed at LPSC Grenoble and is presently being tested. Promising results have already been obtained with ^{87}Rb charge bred to charge state 13+ with efficiencies two times higher than with simple 14 GHz operation [34]. Using appropriate focusing elements prior to the booster, the grounded tube presently used for the injection of the 1+

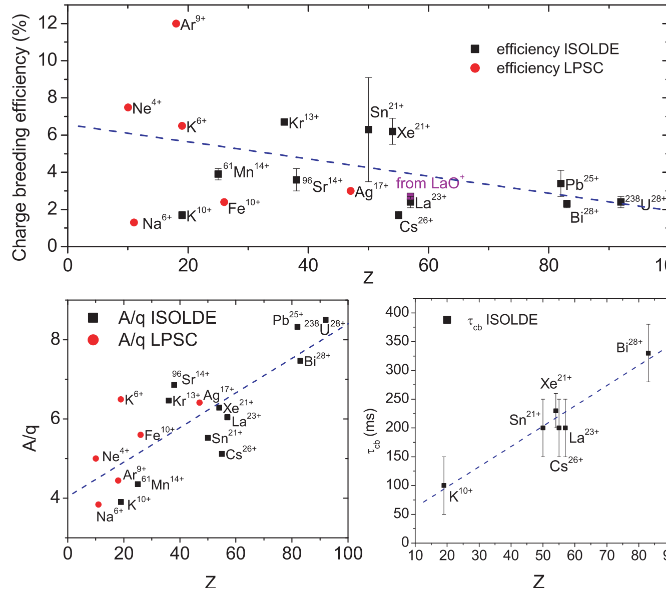

Fig. 9. Summary of the CW mode performances of the Phoenix boosters as measured at ISOLDE and LPSC before its last upgrade (Some results published in [42]).

beam into the ECR plasma theoretically seems to be no longer necessary. This possibility is also being investigated at LPSC. If successful, the injection scheme as well as the high voltage assembly would be significantly simplified, thus easing the maintenance.

2.6 Comparison between the methods

In principle, most charge breeding aspects of the two breeder types as they were discussed in sections 2.4 and 2.5 can be compared. However, it has to be noted that the natural modes of operation of the two charge breeders are significantly different. The results obtained with the ECR afterglow mode are still not sufficient to provide a good basis for the comparison with the inherent pulsed-mode operation of the EBIS, and the partial CW modes tested so far with the EBIS – slow extraction and accu modes - are still far from a true CW mode. For this reason, the performances of the continuous mode of the ECR will be compared to the pulsed mode of the REXEBIS even though their physical meaning can be quite different. A summary can be found in table 6.

From this table, REXEBIS shows a superior performance in terms of the final charge state, rapidity, and beam purity (several orders of magnitude lower background). Also the universality of the method is quite appreciable since the charge breeding of any element is a priori possible: even for light ions the efficiencies are well above the percent level. The rapidity of the charge breeding is especially important for short-lived heavy isotopes, which will be produced in EURISOL-like facilities with intensities suited for experiments. An EBIT-like magnetic configuration allows in addition for spectroscopic investigation of isotopes within the breeder. On the other hand, the ECR

Table 5. Results of charge breeding using the afterglow extraction mode of the Phoenix ECR [41] and MINIMAFIOS [25] ECR charge breeders. q_{max} and A/q_{max} correspond respectively to the most abundant charge state and A/q ratio.

1+ ion	N+ ion	Efficiency %	$\tau_{cb}(\Delta\tau_{cb})$ (ms)	q_{max}	A/q_{max}	Ref.
$^{86}Kr^{+}$	$^{86}Kr^{13+}$	1	500(100)	13	6.6	[41]
$^{132}Xe^{+}$	$^{132}Xe^{18+}$	2.2	600(100)	18	7.33	[41]
$^{85}Rb^{+}$	$^{85}Rb^{15+}$	2.5	520 (Confinement time)	15	5.67	[25]

charge breeder has much higher intensity capabilities; it can be run in CW and pulsed mode; it is robust as a standalone machine and requires very little maintenance. The only fragile part is the RF window, which however can be placed rather far away from the plasma chamber itself. There is in principle no need for a cooler and buncher prior to the charge breeder. These are important issues as a EURISOL facility should be producing much higher intensities than ISOLDE (several orders of magnitude); the superconducting LINAC foreseen is in essence a CW machine; and the hands-on maintenance around the booster may be hindered by the highly radioactive environment.

The comparison of the two methods cannot be limited to the REXEBIS and Phoenix cases. The next section briefly presents a few upgrade and development projects of new charge breeders which are on-going in the world. Some have already shown promising results, such as the upgraded version of the Phoenix developed at LPSC for the SPIRAL 2 project, with results reported in the previous section.

2.7 Charge breeding devices and projects at other facilities

At GANIL, Caen, the Nanogan ECR source situated just after the target is producing multi-charged ions of He, O, F, Ne, Kr and Xe isotopes by capturing, after first ionization, the elements effusing as gaseous atoms or molecules from the target to the ion source volume [45,46]. The multiply charged ions are then post-accelerated by the Cyclotron d'Ions Moyenne Energie (CIME) of the Système de Production d'Ions Radioactifs Accélérés en Ligne (SPIRAL) facility. This simplified production scheme presents some advantages compared to the 1+ n+ scenario since there are no losses due to beam transport and injection from a 1+ source to the charge breeder. Also the beam tuning is simplified. However, in this case the high charge-state ion-source needs to be situated close to the target. Such close coupling introduces some additional issues that need to be solved. For instance, the pressure of the support gas becomes difficult to control as it directly depends on the degassing level of the target. Secondly, the neutron flux generated by the heavy ion beam impinging on the target eventually degrades the performances of Nanogan, whose magnetic confinement is made solely by permanent magnets. Such magnetic configuration results in rather low charge states and overall efficiencies for elements with $Z > 20$ compared to the Phoenix booster. Finally, the production of metallic ions and condensable beams is strongly hindered by the use of a cold transfer section and the small opening angle the ECRIS plasma presents to the target. Future upgrade plans of the SPIRAL 1 facility rely on a true 1+ n+ scenario for enlarging the number of possible beams post-accelerated by CIME. Sources with hot walls such as surface ionization and FEBIAD sources similar to the ones used at ISOLDE will be adapted or developed to permit the production of metallic ions. They will complement the already existing ECRIS 1+ sources from GANIL. The Phoenix booster that was presented in this report will perform the charge breeding. For the SPIRAL 2 project [47] LPSC is developing an upgraded version of Phoenix, for which some very recent results were presented in [34].

At TRIUMF, Vancouver, another Phoenix ECR charge breeder has recently been installed in front of the post-accelerator of the Isotope Separator and ACcelerator (ISAC) II facility for which charge states corresponding to $A/q <$ 7 are required [44,48]. This charge breeder will address the acceleration of heavy ions, while the light ions (A<30) are instead being stripped after a first acceleration stage [49]. The setup is similar to the ones of LPSC and ISOLDE. The main difference though is the addition of an energy separation stage after the mass separation which improves the beam purity substantially. A large part of the stable background after a simple A/q- selection can be explained by ion recombination occurring in the extraction region of the booster, where the recombination to (n-1)+ occurs over a wide range of the extraction potential. In the A/q spectrum, this results in long tails around the A/q peaks. The energy selection removes ions with wrong extraction energy, which results in a reduced level of stable background. With this additional selection stage, a background level less than 100 pA has been observed away from the peaks of C, N, O and other stable contaminants, to be compared with a few nA using the mass separation alone. In addition the TRIUMF setup presents a modified injection optics making use of a two-step deceleration [50]. The first attempt of a multiple electrode deceleration scheme was done at KEK using an ECR source made of permanent magnets [51].

At Argonne National Laboratory, world record efficiencies for ECR charge breeding could be obtained with a charge breeder recently commissioned for the CAlifornium Rare Isotope Breeder Upgrade (CARIBU) project. More than 9% efficiency was obtained injecting $^{85}Rb^{1+}$ ions and charge breeding to the 17+ charge state [52]. There the efficiency was found to be critically influenced by of the residual pressure, and the injection of two frequencies was shown to be beneficial for shifting the charge state distribution to higher charge states. This charge breeder is

Table 6. Comparison of performances of the Phoenix and REXEBIS charge breeders.

	REXEBIS+REXTRAP Pulsed mode	Phoenix booster CW mode
Efficiency	20 → 4%	12 → 2% - broader charge state distribution
τ_{cb}	From 23 to 800 ms depending on A (includes bunching and charge breeding)	100 ms to 300 ms
A/q	2 – 4.5	4 – 8
A	No real limitation	Injection difficult for A <20
Mode	Pulsed or partially CW	Continuous or pulsed
I_{max}	A few nA	$> 10\ \mu$A
Acceptance	EBIS: 11 mm·mrad (95% geometrical) for 60 keV– estimated [15] Trap: $\gtrsim$30 mm·mrad (95% geometrical) for 60 keV– estimated [16]	$\gtrsim$55 mm·mrad at 20 keV (90%) [22]
Beam emittance	15-20 mm·mrad (95% geometrical) for 20 q·keV – measured [13]	<80 mm·mrad at 20 q·keV (90%) [20,34]
Background	Beside residual gas peaks <0.1 pA	Usually >2 nA
Reliability	The cathode is fragile (can be solved with different gun design) and overall system complex	Robust and simple (only ΔV tuning, relatively reproducible settings)

scheduled to be eventually replaced by an EBIS based upon the BNL EBIS design [53].

The charge breeder from the Tokai Radioactive Ion Accelerator Complex (TRIAC) facility, the so-called KEK charge breeder was successfully used for accelerating radioactive ^{92}Kr and ^{126}In [54]. A/q - ratios of about 7 were achieved with charge breeding efficiencies around 7% for noble gases and 2% for condensable elements. More impressively, a very low background could be obtained using a plasma chamber of aluminium which was first sandblasted, then polished by highly-pressurized purified water and finally ultrasonically cleaned. About 600 pps of background were obtained for A/q $\simeq$ 7.68, and less than 100 pps could be measured after the post-accelerator in the A/q operational range ($6 \leq A/q \leq 7$).

Within the European Nuclear Science and Applications Research (ENSAR) I3 proposal an activity has been proposed to test purification methods of intense radioactive beams from ECR charge breeders and ion sources. This activity is supported by several European laboratories: JYFL, Jyväskylä, GANIL and ISOLDE. The use of an ion cooler for optimized injection efficiency and simpler ΔV tuning, UHV components for the charge breeder vacuum system and combined energy and A/q-separation for improving the beam purity were proposed to be tested with the Phoenix ECR charge breeder, as discussed in [42].

An EBIT type charge breeder has been built in collaboration between TRIUMF and the Max Planck Institute for Nuclear Physics at Heidelberg (MPIK) [55] for the TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [56]. TITAN is an ion-trap project making use of highly charged rare isotopes of externally injected ions, in this case produced at ISAC. It is the first high-intensity EBIT system dedicated to charge breeding of externally injected ions. Operated with a 2A electron gun it is expected to provide breeding times close to those of the system discussed in [57]. The TITAN beam line is equipped with a buffer-gas filled RFQ cooler-buncher for singly charged radioactive ions. In addition, a cooler for highly charged ions using protons stored in a large Penning trap is planned in the second stage of the installation. The first highly charged ions were obtained in November 2008, and successful charge breeding tests have been recently performed with radioactive ^{25}Na. A very low electron beam intensity (5 mA) yielded low charge states (2+ as the most populated one).

A similar EBIT-type charge breeder is under construction for the MSU reacceleration facility (ReA3) [14,39,58]. The authors of the first two articles foresee as an option to use two of these EBIT's in push-pull configuration to accommodate a CW operation for the post-accelerating LINAC. The main components of the ReA3 reaccelerator are a high electron current EBIT as a charge breeder; a mass-over-charge separator; a room-temperature RFQ; and a superconducting drift-tube LINAC. Design and construction are in an advanced stage and ReA3 is expected to provide 3 MeV/u beams in 2010. The MSU-EBIT charge breeder has been designed in collaboration with MPIK in Heidelberg and ISAC/TRIUMF. The TITAN EBIT has been the basis for the design but a number of changes have been implemented in order to increase the performance of the system and to optimize it for providing highly-charged ions for reacceleration. The EBIT is mounted on a high-voltage platform with variable potential up to 60 kV. The ions from the gas stopper facility are continuously captured and then charge-bred to the desired charge state. The platform potential is changed prior to extraction to deliver the ions with the correct injection energy of 12 keV/u to the LINAC like in the case of REXEBIS. The hybrid magnet features a short 6 T field region for fast and final charge breeding and an extended field region with lower, variable field strength to optimize the acceptance of the system. With an electron beam current of about 1.5 A available from the present electron gun design and

2.5 A for an extended design, the National Superconducting Cyclotron Laboratory (NSCL) EBIT is a significant step forward to a BNL EBIS type charge state breeder. In the frame of HIE-ISOLDE, i.e. the upgrade of the present REX-ISOLDE facility, REXEBIS could be replaced by a similar charge breeding system.

At GSI a new test bench has been built, which first incorporated the Frankfurt Cryogenic EBIS (MAXEBIS) [59] and later the Stored Particles Atomic Physics Research Collaboration (SPARC) EBIT. The beam line was used to evaluate the suitability of the devices to serve as a test injector for the highly charged Heavy Ion Trap (HITRAP) facility low energy section, which is an essential part of the HITRAP project at GSI [60]. In addition, charge breeding experiments were performed. The SPARC-EBIT and its beam line include a large array of diagnostics: Faraday cups, time-of-flight detector, multichannel plate for beam profile measurements. The open mechanical structure of an EBIT allows for the survey of the ion charge - state development via detection of characteristic X-rays emitted from highly charged ions inside the electron beam. A Si X-ray detector attached to the Be-window of the SPARC-EBIT pointing to the centre of the trap region, was available and spectra of externally injected ions could be recorded.

In addition to EURISOL Design Study, both charge breeding techniques have benefited from the I3 EURONS where advanced charge breeding techniques were developed. The EURONS studies comprised, for instance, compression of the charge-state distribution in an EBIS, an increase of charge breeding efficiencies and beam purification methods for both breeders [11],[34]. Several overviews of these specific charge breeding activities have been presented at conferences, the last two treating both EBIS and ECRIS charge breeders [31],[61].

3 Charge breeding for EURISOL

Based on the comparison of Phoenix and REXEBIS performances (section 2.6), and on the initial results or concepts proposed for upgraded versions of both breeder types around the world (section 2.7), a pragmatic solution can be suggested for the charge breeding system of EURISOL.

3.1 Scope of EURISOL

EURISOL aims at post-accelerating very intense as well as very exotic and low-intensity radioactive nuclear beams [62] up to 100 A·MeV with a superconducting LINAC which is highly suited to CW operation. Most intense neutron-rich beams such as $^{132}Sn^{1+}$ are expected to be produced by a multi-megawatt uranium carbide target, with intensities as high as several 10^{13} ions per second. These beams should be used for producing even more neutron rich nuclides by “cold fragmentation”. Besides these, very exotic neutron rich nuclides such as ^{74}Ni, or neutron deficient beams such as ^{62}Ga, are to be produced respectively as fission fragments or by target fragmentation using 100 kW targets. In these cases the expected intensities are much lower ($<10^6$ particles/s). While for the most intense beams the use of an ECRIS charge breeder seems required, the rare isotope beams would benefit from the use of an EBIS because of its inherent superior beam purity. Moreover, higher charge states attainable in the EBIS within short charge breeding times could compensate in particular for the unfavourable A/Z - ratio of very neutron rich nuclides.

3.2 Proposed solution

In principle, a configuration where both an ECRIS and an EBIS charge breeder system are placed in parallel would permit to make optimum use of the complementary performances of both devices. Such configuration is possible and is described in detail in [63]. As the EURISOL post-accelerator is a superconducting LINAC, two EBIS charge breeders rather than one would allow for a pseudo-CW operation, as envisaged for FRIB [14,39,58]. In this case, the accu-mode and slow extraction mode mentioned in section 2.4 would have to be combined, thus permitting a continuous accumulation of the 1+ ions and release of the charge bred ions as flat as possible in time. The high potential of both charge breeders is fixed during injection by the energy of the 1+ ions. For an optimum capture of the 1+ ions, it is equal to the high potential of the 1+ source minus ΔV for the ECRIS or a few tens of volts for the EBIS. The energy of the charge bred ions then needs to be adapted to the velocity acceptance of the RFQ of the post-accelerating LINAC. In the case of the EBIS, this adaptation can easily be done by switching the high potential of the charge booster from one voltage to another between injection and extraction, as it is done at REX-ISOLDE. In the case of the ECRIS charge breeder, it is imagined that the RFQ of the superconducting LINAC can be placed on a HV platform for compensating for the energy mismatch, as proposed in [64].

3.3 Conclusions

The study presented here was realized within the frame of the EURISOL Design Study. It has resulted in a comprehensive evaluation of existing ECRIS and EBIS based charge breeders. EURISOL, as an ambitious ISOL - facility project, aims at the post-acceleration of very intense radioactive beams as well as rare short-lived isotopes. Therefore its breeding system should be capable of handling both. After a compilation of results obtained with the two charge breeder systems at ISOLDE (the Design Study breeders), this document presented a brief overview of representative charge breeding projects around the world. Apart from EURISOL, many facilities are presently investigating or developing EBIS/T and ECRIS charge breeders as is attested in [61]. Among them, SPIRAL 2, SPES, the CARIBU project and TRIUMF/ISAC will use ECRIS charge breeders. On the other hand MSU is developing an EBIT charge breeder for FRIB based on a design similar to the TITAN-EBIT, and the SPARC-EBIT is being commissioned for GSI/HITRAP. In this context the two techniques of charge breeding are expected to evolve rapidly. Second generation ECRIS and EBIS charge breeders are already being built or tested.

Based on this information, a solution has been proposed that should satisfy the needs of a future EURISOL facility by using both charge breeders types in parallel and their complementary features. In summary the abilities of both breeder systems are:

1. Charge states yielding mass-to-charge ratios between A/q=2-3 and A/q=7 can be obtained for all elements in the chart of nuclides, with lowest A/q for EBIS.
2. Efficiencies well above the percent range for any A, Z range can be obtained, with a wide range of isotopes for which the efficiencies are around or higher than 5%. ECRIS breeders cover masses above 20 while EBIS systems cover the whole chart of isotopes.
3. The charge breeding times are well below one second (whatever choice of charge breeder), which is shorter than or similar to the typical diffusion-effusion times from ISOL targets. Very short breeding times for short lived isotopes, down to the ms region with an EBIS breeder, are a priori possible.
4. Intense radioactive beams - up to 10^{13} ions/s - can be charge bred without loss of efficiency by ECRIS charge breeders.
5. Exotic beams of medium to low intensity – as low as 10^2-10^3/s – can be charge bred by the EBIS keeping a very good beam purity.
6. CW operation of the superconducting LINAC will be possible using the natural mode of operation of the ECRIS charge breeder, and two EBIS charge breeders in "push-pull" mode.

In the future, the performances of ECRIS and EBIS may overlap more and more. For instance, one should expect purified beams from ECR charge breeders and true CW operation from EBIS charge breeders. It is not yet clear where the exact frontier between the two techniques and their domain of application will be. The numbers given above are only indicative, and both techniques are expected to exhibit improved performances with time as experience is gained and numerous developing goals are achieved.

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